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Providing electricity access to remote areas in India: An approach towards identifying potential areas for decentralized electricity supply

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Abstract

This study presents the results of a preliminary attempt towards identifying potential areas in India where provision of electricity through renewable energy-based decentralized generation options can be financially more attractive as compared to extending the grid. The cost of generation of electricity from coal, hydro and nuclear power plants and also cost of transmission and distribution of electricity in the country have been estimated. The delivered cost of electricity (generated in a coal thermal power plant) in remote areas, located in the distance range of 5–25 km is found to vary in a wide range varying from Rs.[1] 3.18 to 231.14/kWh depending on peak electrical load and load factor. The study indicates that renewable energy-based decentralized electricity supply options (such as micro hydro, dual fuel biomass gasifier systems, small wind electric generators and photovoltaics) could be financially attractive as compared to grid extension for providing access to electricity in small remote villages.
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Keywords: Rural electrification; Decentralized electricity generation options; Delivered cost of electricity; Critical distance for grid extension

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Contents

1. Introduction

Electricity is one of the critical inputs for overall development of a country and is one of the main infrastructural requirements for agricultural, industrial and socio-economic development and also for employment generation in rural and remote areas. In most parts of the world, areas without electricity are far less developed than those with electricity [1]. Electricity is an input to the production of outputs that contribute directly to households well being; that is, electricity is desired not for its own sake, but for its ability along with appliances, to produce goods and services that are more directly desired. Hence, efficient provision of electricity contributes to poverty reduction by spurring economic growth and fulfilling human needs of health and education. For rural populations the positive effects of electricity inputs for basic activities such as pumping water for drinking and

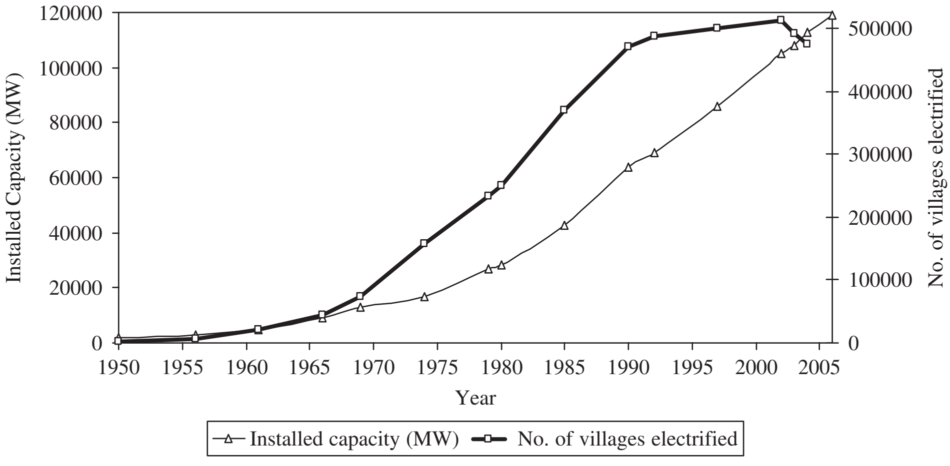

Fig. 1. Time trend of installed power-generating capacity and village electrification in India.

irrigation; lighting for increasing working hours in the evening; and carrying out operations in small-scale rural industry are considerably greater due to bundling of economic benefits [2]. Providing access to electricity in remote areas has been regarded synonymous with rural electrification, implemented through the extension of the grid [3]. Rural electrification is a declared objective of the central and state governments in India and has been accorded high degree of priority [4]. The problems of high transmission and distribution (T&D) losses; frequent disruption in supply of grid power, practical difficulties and financial un-viability of extending grid to remote and inaccessible areas; dispersed population in small villages resulting in low peak loads in rural and remote areas, poor financial health of the state electricity boards, etc. are plaguing the rural electrification program in India [2–5]. The progress of village electrification which was rapid up to 1990, slowed down considerably thereafter due to the above-mentioned factors though power-generating capacity continued to grow by about 3–6% annually [6]. Fig. 1 shows the time trend of growth of installed power-generating capacity and number of electrified villages in India.

The National Electricity Policy (NEP) for India, announced in February 2005, addresses the issue of rural electrification [7]. NEP states the commitment of the government of India to ensure that the task of rural electrification for securing electricity access to all households and also ensuring that electricity reaches the disadvantaged sections of the society at an affordable price by 2010. For achieving this objective, wherever providing grid connectivity would not be cost-effective, decentralized electricity generation with local distribution network would be provided. In the context of providing electricity access to all un-electrified villages particularly remote and inaccessible villages in India, the relevance of decentralized generation has also been recognized by a committee set up by the government [4]. NEP emphasizes that for decentralized electricity generation both renewable energy based as well as conventional (non-renewable) technologies, whichever is suitable and economical, would be deployed. Renewable energy-based technologies would be considered even where grid connectivity exists, provided it generates cost-effective electricity. NEP envisages that for achieving targeted expansion in access to electricity for rural households in the desired time frame, distribution licensees would need

to recover at least the cost of electricity and related operation and maintenance (O&M) expenses from consumers, except for lifeline support to households below the poverty line (who would need to be adequately subsidized).

Much before the announcement of the NEP in 2005, a remote village electrification program was started by the Ministry of Non-Conventional Energy Sources (MNES) of Government of India in 2001–2002 for providing electricity access to remote villages where extension of electricity grid may not be possible in the near future [8]. The remote villages are proposed to be provided with electricity supply from renewable energy-based decentralized generation options such as small hydro, biomass gasifiers, photovoltaics (PV), wind energy conversion systems, hybrid systems, etc.

In spite of known advantages of renewable energy-based electricity generation options especially in view of their suitability for decentralized applications and environmental sustainability, the most economical electricity generating/supply and sustainable option would be accepted in long term. This becomes all the more important as financial viability of renewable energy-based options for power generation is highly site dependent. This paper makes an attempt towards identifying potential areas in India where electricity can be generated and supplied through renewable energy-based decentralized generation options instead of extending the grid by undertaking a comparison of the indicators of financial performance such as unit capital cost of different options and the levelised unit cost of electricity (LUCE) of both the options.

2. Status and growth of power sector in India

Electricity is covered under the concurrent list in the Constitution of India, which implies that both the central as well as the state governments have the jurisdiction to legislate on the power sector. At the time of India's independence in 1947, the total installed capacity for electricity generation was only 1362 MW and merely 1500 villages had access to electricity [6,9]. The Indian power sector has made a significant growth since independence in terms of (a) installed electricity generating capacity, (b) per capita electricity consumption, and (c) village electrification [10]. Fig. 2 shows the time trend of growth of per capita electricity consumption in India and along with Fig. 1 exemplifies the growth of the power sector in India. The sudden drop in number of villages considered to be electrified at the end of 2003–2004 in Fig. 1 is attributed to the change in the definition[2] of an 'electrified village' by the Ministry of Power in October 1997. The number of villages considered to be electrified in the country may further come down in view of a new definition[3] adopted by the government of India in 2004–2005.

[2]"a village will be deemed to be electrified if electricity is used in the inhabited locality within the revenue boundary of the village for any purpose whatsoever" from the earlier definition "a village is classified as electrified if electricity is being used within its revenue area for any purpose whatsoever."

[3]The new definition adopted by the Ministry of Power for electrified village from 2004–2005 is as per below:

(1) Basic infrastructure such as distribution transformer and distribution lines are provided in the inhabited locality as well as the Dalit Basti/hamlets where it exists (for electrification through non-conventional energy sources a distribution transformer may not be necessary).
(2) Electricity is provided to public places like schools, panchayat office, health centres, etc., and
(3) The number of households electrified should be at least 10% of the total number of households in the village.
(4) Compulsory certification from Gram Panchayat regarding the completion of village electrification should be obtained.

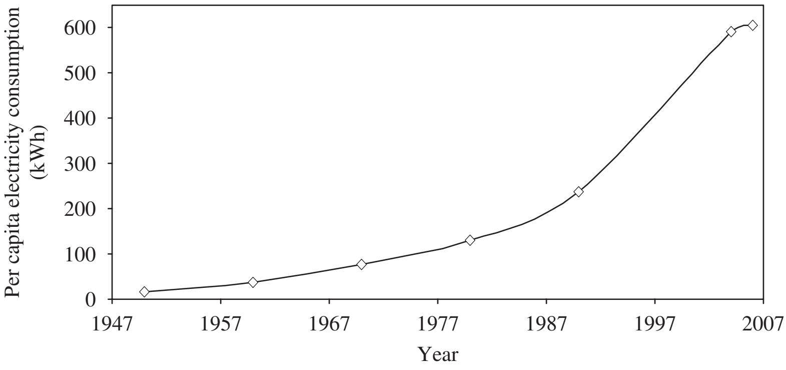

Fig. 2. Time trend of per capita electricity consumption in India.

The total installed power-generating capacity of utilities in India from hydro, thermal (coal, gas and diesel), renewables and nuclear stood at 124,286.8 MW as on 3 April 2006 as per state wise details given in Table 1 [10]. The demand for power is outstripping its availability and therefore, the shortages in peak electricity demand (11,650 MW) and energy supply (26,793 million kWh) in the country during the period April–September 2006 were about 8.0% and 12.2%, respectively [11]. This is due to inadequacies in generation, T&D as well as inefficient use of electricity [7].

Moreover, resources for electricity generation are unevenly dispersed across the country leading to mismatch in demand and supply in some regions. Besides the installed power-generating capacities of the utilities, as per the estimates of the Central Electricity Authority a total captive power-generating capacity of 41,740 MW was existing in India as on 31 March 2004, of which 23,000 MW was constituted by power-generating units of capacity less than 1 MW essentially installed as back up power supply sources [12].

The history of evolution and development of renewables in India is as old as the history of power development in India and goes back to about 110 years. It started with installation of the first small hydro power (SHP) project of 130 kW capacity at Sidrapong near Darjeeling in the state of West Bengal in 1897 followed by other installations. The earliest two micro hydro power projects implemented in the country were of 40 kW capacity and 50 kW capacity, respectively at Chamba (in 1902) and Jubbal (in 1911) [13]. In the absence of high-voltage transmission lines, the SHP projects were set up primarily to meet electricity demand for lighting of nearby towns in decentralized manner. The interests in renewables other than SHP started much later in 1970s when the quest for alternative energy sources began in the wake of the first oil shock. India has an independent ministry (Ministry of New and Renewable Energy, known as Ministry of Non-Conventional Energy Sources prior to October 2006) in the central government, set up in 1992, for dealing with matters related to new and renewable sources of energy [14]. The importance attached by the government of India to new and renewable energy sector has resulted in a significant growth of this sector in India. The share of electricity-generating capacity based on renewables has been increasing steadily in India and they contribute 7170.98 MW aggregate capacity as on 31 December 2005 as per details given in Table 2 [14].

An extensive network of T&D lines has been developed over the years in the country for evacuating power produced from various electricity-generating stations and distributing it

Table 1
Installed power generating capacity (MW) in the India as on 3 April 2006

State	Hydro	Thermal				Renewables	Total
		Coal	Gas	Diesel	Total		
Delhi	0	320	612.4	0	932.4	0.07	932.47
Haryana	946.64	1602.5	0	3.92	1606.42	7.36	2560.42
Himachal Pradesh	709	0	0	0.13	0.13	49.09	758.22
Jammu and Kashmir	309.15	0	175	8.94	183.94	11.11	504.2
Punjab	2474.72	2130	0	0	2130	144.95	4749.67
Rajasthan	1008.84	2420	113.8	0	2533.8	323.47	3866.11
Uttar Pradesh	518.6	4280	0	0	4280	125.77	4924.37
Uttaranchal	986.93	0	0	0	0	32.77	1019.7
Chandigarh	0	0	0	2	2	0	2
Goa	0	0	48	0	48	0.07	48.07
Daman and Diu	0	0	0	0	0	0	0
Gujarat	745	5069	1908.72	17.48	6995.2	306.88	8047.08
Madhya Pradesh	1586.66	2157.5	0	0	2157.5	51.19	3795.35
Chhattisgarh	125	1280	0	0	1280	34.01	1439.01
Maharashtra	3224.66	8075	1832	0	9907	706.68	13,838.34
Dadra and Nagar Haveli	0	0	0	0	0	0	0
Andhra Pradesh	3586.36	2952.5	1738.4	36.8	4727.7	545.29	8859.35
Karnataka	3427.9	1730	220	234.42	2184.42	916.92	6529.24
Kerala	1807.6	0	174	256.44	430.44	48.85	2286.89
Tamilnadu	2145.85	3220	919.3	411.66	4550.96	2721.83	9418.64
Pondicherry	0	0	32.5	0	32.5	0.6	33.1
Bihar	44.9	553.5	0	0	553.5	30.42	628.82
Jharkhand	130	1620	0	0	1620	4.13	1754.13
West Bengal	161.7	4386.38	100	12.2	4498.58	66.65	4726.93
Orissa	1923.93	420	0	0	420	1.37	2345.3
Sikkim	32	0	0	5	5	9.1	46.1
Assam	2	330	269	20.69	619.69	0.23	621.92
Arunachal Pradesh	18.5	0	0	15.88	15.88	25.98	60.36
Meghalaya	185.52	0	0	2.05	2.05	1.51	189.08
Tripura	16	0	127.5	4.85	132.35	1.11	149.46
Manipur	1.5	0	0	45.41	45.41	3.95	50.86
Nagaland	25.5	0	0	2	2	3.17	30.67
Mizoram	4	0	0	51.86	51.86	10.91	66.77
Andaman and Nicobar	5.25	0	0	60.05	60.05	5.42	70.72
Lakshadweep	0	0	0	9.97	9.97	0	9.97
Central Sector	6172	25,972.43	4419.03	0	30,391.46	0	39,923.46[a]
Grand total	32,325.71	68,518.81	12,689.65	1201.75	82,410.21	6190.86	124,286.8[a]

Source: [10] (as on 3 April 2006).
[a]Includes 3360 MW of nuclear power generating capacity in the central sector.

to the consumers. Depending on the quantum of power and distance over which the electricity is to be transmitted, transmission lines of appropriate voltages have been laid. The nominal voltage of transmission lines are 500 kV HVDC, 400, 230/220, 110 and 66 kV. The standard voltages on the distribution sides are 33, 22, 11 kV and 400/230 V besides 6.6, 3.3 and 2.2 kV. The low-voltage system has three-phase four-wire supply (400/420 V) and single-phase two-wire supply (230/240 V). The lengths of T&D

Table 2
Power generating capacity based on renewables set up in India as on 31 December 2005

Sl. No.	Type of power generation	Installed capacity (MW)
(A) *Grid interactive power based on renewables*		
1.	Bagasse co-generation	491.00
2.	Biomass gasifier	1.00
3.	Biomass power	376.53
4.	Power from wastes	34.95
5.	Small hydro power (up to 25 MW)	1747.98
6.	Solar photovoltaic power	2.74
7.	Wind power	4433.90
(B) *Decentralized power based on renewables*		
8.	Biomass gasifiers	69.87
9.	Power from wastes	11.03
10.	Solar photovoltaic power plants	1.57[a]
11.	Small wind electric generators and wind–photovoltaic systems	0.41
Total		7170.98

Source: [14].
[a]Excluding solar home systems (342,607 nos.), solar street lighting systems (54,795 nos.) and solar lanterns (538,718) which are estimated to have an aggregate capacity of about 22 MW_p.

Table 3
Length of electricity transmission and distribution networks in India as on 31 March 2004

Voltages	Length of lines (Circuit kms.)
HVDC 500 kV	5876
400 kV	53,616
230/220 kV	101,667
132/110/90 kV	121,925
78/66 kV	53,297
33/22 kV	283,240
15/11 kV	1,869,371
6.6/3.3/2.2 kV	6362
Distribution lines up to 500 V	3,859,504

Source: [21].

lines in India as on 31 March 2004 are given in Table 3. The total numbers of step-up, step-down and distribution transformers installed in the country as on 31 March 2004 with their aggregate capacity were respectively 1952 (130,433,600 kVA); 32,291 (422,137,932 kVA); and 2,492,274 (206,667,870 kVA). The entire power system in the country is divided into five regions. A pool structure exists in each region with regional electricity boards for facilitating the integrated operation of the power system in the region and for exchange of power with other regions and regional load dispatch centers (RLDC). The RLDCs are operated by the National Power Grid Corporation, a public sector company engaged in transmission of electricity in India [15].

3. Rural electrification in India

In-spite of a significant growth made by power sector in India since 1947, more than 35% of the world's population without having access to electricity was living in India in 2000, majority of which lives in rural areas [16]. The challenges involved in providing electricity access in rural areas of India could be understood by the fact that whereas 80.80% of the villages (474,982 out of 587, 556 inhabited villages as per 1991 census) were considered to be electrified (as per prevailing definition of village electrification then) as on 31 March 2004 (Table 4), only about 43.5% of rural households (60.18 million out of 138.27 million) had access to grid supplied electricity as per 2001 census data (Table 5). About 66.5% of the households not having access to electricity were located in only six states i.e. Uttar Pradesh (21.14%), Bihar (15.38%), West Bengal (11.40%), Orissa (7.00%), Andhra Pradesh (6.55%) and Rajasthan (5.13%).

A total of 112,401 villages were not having access to electricity as on 31 March 2004 (Table 4). Government of India has envisaged providing electricity access to these villages and all households in the country by 2010 [9]. Therefore, high priority is being attached to the implementation of rural electrification in India by the governments. Rural electrification program is implemented by the States and Union Territories in their respective areas and is also supported by the Rural Electrification Corporation [17]. The focus of rural electrification program is on electrification of all villages and rural households and improve irrigation through energisation of pump sets.

Nearly 24,500 villages out of 112,401 un-electrified villages are classified in the category of 'remote villages' where extension of the conventional electricity grid may not be possible in the near future [8]. All these remote villages are proposed to be provided with electricity supply from renewable energy-based decentralized generation options. The NEP also envisages reliable rural electrification systems through decentralized generation facilities together with local distribution network to ensure that every household gets access to electricity wherever it is not feasible and cost effective to provide grid connectivity [7].

4. Delivered cost of electricity in rural areas through grid extension

The most preferred method of augmenting electricity supply is by setting up the centralized power plants and transporting electricity so generated to the point of consumption through existing or by laying new T&D network. At any location receiving electricity through grid, the delivered cost of electricity comprises of three components i.e. (a) cost of generation of electricity at the bus bar of the centralized plant; (b) cost of transmitting electricity through the transmission network; and (c) cost of distribution. The contributions to the delivered LUCE by these components of cost have been estimated based on the base values of the input parameters as given in Table 6. The base values of input parameters have been selected based on the values reported in the literature.

4.1. Cost of electricity generation

Among the centralized power-generating options based on thermal, hydro and nuclear plants, coal thermal and large-capacity hydro power plants (HPPs) (greater than 25 MW capacity) are contributing 55.13% and 26.01% of installed power-generating capacity as on 3 April 2006 (Table 1). Government of India is attaching considerable importance to

Table 4
Status of village electrification in India as on 31 March 2004

Name of State/UT	No. of inhabited villages as per 1991 census	Total no. of electrified villages	Un-electrified villages	% of electrified villages
Andhra Pradesh	26,586	26,565	21	99.92
Arunachal Pradesh	3649	2335	1314	63.99
Assam	24,685	19,081	5604	77.30
Bihar	38,475	19,251	19,224	50.03
Jharkhand	29,336	7641	21,695	26.04
Goa	360	360	—	100.00
Gujarat	18,028	17,940	88	99.51
Haryana	6759	6759	—	100.00
Himachal Pradesh	16,997	16,891	106	99.38
Jammu and Kashmir	6477	6301	176	97.28
Karnataka	27,066	26,771	295	98.91
Kerala	1384	1384	—	100.00
Madhya Pradesh	51,806	50,474	1332	97.43
Chhattisgarh	19,720	18,532	1188	93.97
Maharashtra	40,412	40,351	61	99.85
Manipur	2182	2043	139	93.63
Meghalaya	5484	3016	2468	55.00
Mizoram	698	691	7	99.00
Nagaland	1216	1216	—	100.00
Orissa	46,989	37,663	9326	80.15
Punjab	12,428	12,428	—	100.00
Rajasthan	37,889	37,276	613	98.38
Sikkim	447	405	42	90.60
Tamilnadu	15,822	15,822	—	100.00
Tripura	855	818	37	95.67
Uttar Pradesh	97,122	57,042	40,080	58.73
Uttaranchal	15,681	13,131	2550	83.73
West Bengal	37,910	31,705	6205	83.63
Total States	586,463	473,892	112,571	80.80
Total UTs	1093	1090	3	99.73
All India	587,556	474,982	112,574[a]	80.84

Source: [9].
[a]As per the new definition of village electrification (effective from 2004–2005) total number of un-electrified villages is estimated to be around 125,000.

nuclear power generation from the point of view of energy security in the long run though it contributes only 2.7% of installed power-generating capacity presently [18].

4.1.1. Pit head coal thermal power plants (CTPPs)

The total capital cost estimates and unit capital cost of some coal-based thermal power projects (210–1980 MW) that have either been set up since 2002 or which are expected to be commissioned by 2008 in India by the National Thermal Power Corporation (NTPC), a central electricity utility are given in Table 7 [19]. Most of these thermal power plants are located near pit heads. NTPC owned 20 operating coal and gas/liquid fuel power plants of

Table 5
Rural households having access to electricity in India as per 2001 census

Name of State/ Union Territories	Total no. of rural households	Households having access to electricity	% of households having access to electricity	Households not having access to electricity	% of total un-electrified households in India
Andhra Pradesh	12,676,218	7,561,733	59.65	5,114,485	6.55
Arunachal Pradesh	164,501	73,250	44.53	91,251	0.12
Assam	4,220,173	697,842	16.54	3,522,331	4.51
Bihar	12,660,007	649,503	5.13	12,010,504	15.38
Jharkhand	3,802,412	379,987	9.99	3,422,425	4.38
Goa	140,755	130,105	92.43	10,650	0.01
Gujarat	5,885,961	4,244,758	72.12	1,641,203	2.10
Haryana	2,454,463	1,926,814	78.50	527,649	0.68
Himachal Pradesh	1,097,520	1,036,969	94.48	60,551	0.08
Jammu and Kashmir	1,161,357	868,341	74.77	293,016	0.38
Karnataka	6,675,173	4,816,913	72.16	1,858,260	2.38
Kerala	4,942,550	3,238,899	65.53	1,703,651	2.18
Madhya Pradesh	8,124,795	5,063,424	62.32	3,061,371	3.92
Chhattisgarh	3,359,078	1,548,926	46.11	1,810,152	2.32
Maharashtra	10,993,623	7,164,057	65.17	3,829,566	4.90
Manipur	296,354	155,679	52.53	140,675	0.18
Meghalaya	329,678	99,762	30.26	229,916	0.29
Mizoram	79,362	35,028	44.14	44,334	0.06
Nagaland	265,334	150,929	56.88	114,405	0.15
Orissa	6,782,879	1,312,744	19.35	5,470,135	7.00
Punjab	2,775,462	2,482,925	89.46	292,537	0.37
Rajasthan	7,156,703	3,150,556	44.02	4,006,147	5.13
Sikkim	91,723	68,808	75.02	22,915	0.03
Tamilnadu	8,274,790	5,890,371	71.18	2,384,419	3.05
Tripura	539,680	171,357	31.75	368,323	0.47
Uttar Pradesh	20,590,074	4,084,288	19.84	16,505,786	21.14
Uttaranchal	1,196,157	602,255	50.35	593,902	0.76
West Bengal	11,161,870	2,262,517	20.27	8,899,353	11.40
Andaman and Nicobar Islands	49,653	33,807	68.09	15,846	0.02
Chandigarh	21,302	20,750	97.41	552	0.00
Dadra and Nagar Haveli	32,783	27,088	82.63	5695	0.01
Delhi	169,528	144,948	85.50	24,580	0.03
Daman and Diu	22,091	21,529	97.46	562	0.00
Lakshadweep	5351	5337	99.74	14	0.00
Pondicherry	72,199	58,486	81.01	13,713	0.02
All India	138,271,559	60,180,685	43.52	78,090,874	100.00

Source: [9].

Table 6
Base values of input parameters used for estimating levelised unit cost of electricity generation for thermal, hydro and nuclear power plants and cost of distribution of electricity

Input parameter	Unit	Value
Cost of repair and maintenance of electricity distribution network as a fraction of its capital cost	Fraction	0.05
Cost of operation and maintenance of thermal power plants as a fraction of its capital cost	Fraction	0.04
Cost of operation and maintenance of hydro power plants as a fraction of its capital cost	Fraction	0.04
Cost of operation and maintenance of nuclear power plants as a fraction of its capital cost	Fraction	0.02
Discount rate	Fraction	0.10
Distance of 11 kV line as fraction of distribution network	Fraction	0.50
Distance of LT line 3 phase 4 wire as fraction of distribution network	Fraction	0.25
Distance of LT line single phase 2 wire as fraction of distribution network	Fraction	0.25
Life of distribution network	Years	25[a]
Life of large hydro power plant	Years	50[a]
Life of nuclear power plant	Years	40[b]
Life of thermal power plant	Years	30[b]

[a][36].
[b][18].

aggregate capacity of about 24,500 MW as on 30 June 2005. The capital cost of installing the CTPPs is in the range of Rs. 36.4–44.7 million/MW depending rated capacity of units of CTPP and total installed capacity planned at the project.

4.1.2. Load center CTPPs

In the case of CTPPs set up near the load centers, the delivered cost of coal would depend on the distance between the power plants and the coal mines. The delivered costs of coal for two types of coal (based on their calorific values) at CTPP with variation in the distance by which coal is to be transported from the coal mine by rail are presented in Fig. 3 [20].

4.1.3. Plant load factor (PLF)

There is wide variation in the PLF of the CTPPs owned and managed by the central, state and private utilities in India. During 2004–2005 the average values of PLF for these utilities were, respectively 81.45%, 69.77% and 85.12%. The national average PLF during 2004–2005 was 74.82% [21]. The national average PLF has shown a marked improvement from 55.30% to 74.82% during the period 1991–1992 to 2003–2004 [21,22].

4.1.4. Electricity output of power plants at bus bar

The annual delivered electricity output (E_o) at bus bar of any power plant (for one power-generating unit) with rated power output (P) of electricity generator of the unit is dependent on its PLF and the fraction of generated power consumed by the auxiliaries of the power plant (a). E_o can be estimated using the following expression:

$$E_o = 8760 \times (1 - a) \times \mathrm{PLF} \times P. \tag{1}$$

Table 7
Estimated investment requirement for setting up thermal power plants (by NTPC)

Name of project	Capacity (MW)	Time period of commercial operation	Approved cost	
			Total (Million Rupees)	Per unit capital cost (Million Rupees/MW)
Simhadri	1000	Nov. 2002 and March 2003	36,507.9	36.5
Rihand stage II	1000	2004–2005	40,494.9	40.5
Vindhyachal stage III	1000	2006–2007	42,015.0	42.0
Ramagundam stage III	500	2004–2005	18,184.6	36.4
Unchahar	210	2006–2007	9392.8	44.7
Sipat St-I	1980	2007–2008, 2008–2009	83,233.9	42.0
Sipat St-II	1000	2007–2008	40,396.4	40.4

Source: [19].

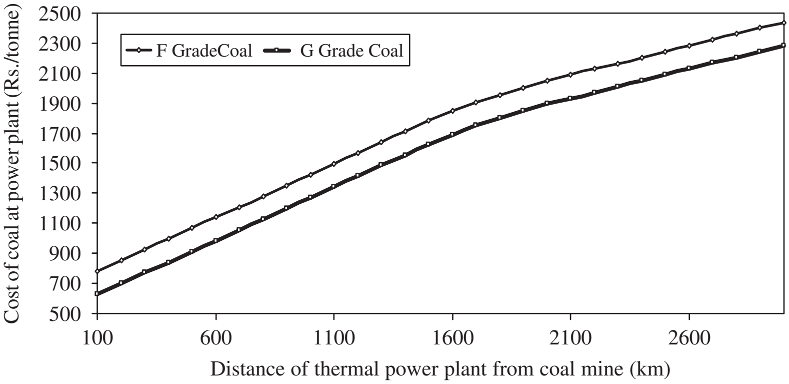

Fig. 3. Delivered cost of electricity to load center thermal power plants in India.

4.1.5. Station heat rate and specific coal consumption of CTPPs

If h is the heat rate (total heat input to be provided by oil and coal for generating 1 kWh of electricity) of the CTPP, o_{soc} the specific fuel oil consumption, CV_o the average calorific value of fuel oil and CV_c the average calorific value of coal, then the specific coal consumption (c_{scc}) can be estimated by the following expression:

$$c_{scc} = \frac{h - o_{soc} \times CV_o}{CV_c}. \tag{2}$$

4.1.6. LUCE from CTPPs

The LUCE is one of the commonly used indicators for financial performance evaluation for power-generating plants such as CTPPs. The LUCE generation for a CTPP $(LUCE_g)_{ct}$

can be estimated as the ratio of the total annualized cost of the CTPP to the annual electricity output at the bus bar of the same, i.e.

$$(\mathrm{LUCE_g})_{\mathrm{ct}} = \frac{C_\mathrm{o} \times \mathrm{CRF} + 8760 \times \mathrm{PLF} \times P(c_{\mathrm{scc}} \times p_\mathrm{c} + o_{\mathrm{soc}} \times p_\mathrm{o}) + m \times C_\mathrm{o}}{E_\mathrm{o}}, \tag{3}$$

where C_o is the capital cost of the CTPP, CRF the capital recovery factor, p_c the average unit cost of coal, p_o the average unit cost of oil and m a fraction of capital cost of the CTPP.

The generation cost for 2 × 500 MW Simhadri thermal power plant owned and operated by the NTPC has been estimated at Rs. 1.71/kWh (Appendix A.1). The variation in the LUCE of a typical 500 MW unit (average capital cost Rs. 40 million/MW) of CTPP set up near load center with variation in distance by which the coal is to be transported from coal mine to the CTPP is depicted in Fig. 4.

4.1.7. *Cost of generation from large HPPs*

The LUCE generation $(\mathrm{LUCE_g})_\mathrm{h}$ for large HPP of the rated capacity of P can be estimated by the following expression:

$$(\mathrm{LUCE_g})_\mathrm{h} = \frac{C_\mathrm{o} \times \mathrm{CRF} + m \times C_\mathrm{o}}{E_\mathrm{o}}, \tag{4}$$

where C_o is the capital cost of HPP, CRF the capital recovery factor, m a fraction of capital cost of HPP and E_o the annual electricity output of HPP at bus bar. The cost of electricity generation from the 3 × 100 MW Chamera II HPP commissioned by the National Hydro Electric Corporation, a public sector utility, in 2003–2004 has been estimated at Rs. 1.84/kWh (Appendix A.2). The unit capital cost of HPPs may vary considerably due to variations in the cost of civil works, which is site specific.

4.1.8. *Cost of generation from nuclear power plants (NPPs)*

For NPPs that have been installed and are operating in India not much of the cost-related information such as capital cost of NPPs, cost of fuel (uranium) and heavy water used in the NPPs, and O&M costs are available in the literature. The LUCE generation

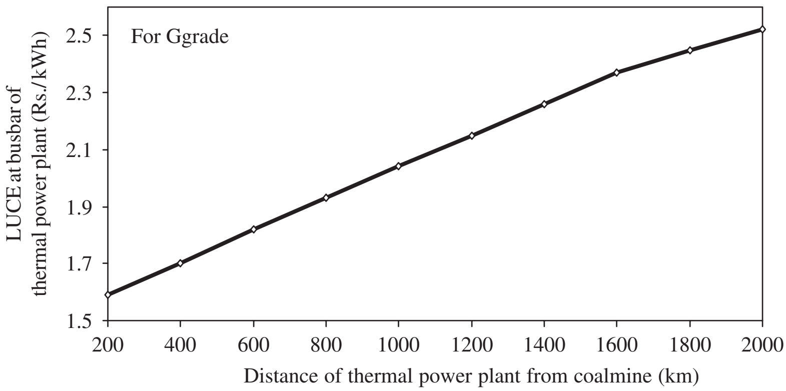

Fig. 4. Levelised unit cost of electricity from the load center thermal power plants in India.

from NPPs $(\mathrm{LUCE_g})_n$ has been estimated using the following expression:

$$(\mathrm{LUCE_g})_n = \frac{C_o \times \mathrm{CRF} + 8760 \times \mathrm{PLF} \times P \times (\mathrm{nf_{suc}} p_u) + \mathrm{hw_l} \times p_{hw} + m \times C_o}{E_o}, \quad (5)$$

where C_o is the capital cost of NPP, CRF the capital recovery factor, $\mathrm{nf_{suc}}$ the specific uranium utilization, p_u the cost of uranium, $\mathrm{hw_l}$ the yearly loss of heavy water, p_{hw} the cost of heavy water, m a fraction of the annual capital cost of NPP and E_o the annual electricity output of NPP. The cost of generation of electricity from 220 and 540 MW nuclear power-generating units that have become or likely to become operational in Kaiga (III and IV units) and Tarapur Atomic Power Station (III and IV units), respectively have been estimated based on the cost and other operational information of NPPs [18,23] and are found to be Rs. 2.46 and 2.19/kWh, respectively for 220 and 540 MW nuclear power-generating units (Appendix A.3).

4.1.9. Comparison of electricity generation costs of centralized power plants

The cost of generation from centralized power plants broadly comprises of O&M cost, fuel cost and capital cost. A comparison of the cost of electricity on the basis of the above-mentioned components of cost for thermal, hydro (no fuel cost) and NPPs is depicted in Fig. 5. The LUCE for CTPP is the most attractive among the three options compared in this paper.

4.1.10. Cost of electricity generation considered in the study

Considering the long gestation periods for setting up large HPPs and NPPs, the deficit in demand and supply of electricity would mainly be bridged in a short time period by setting up new CTPPs, even though gas-based thermal power plants have also been set up in the country in the last two decades. Though the contribution of gas-based thermal power-generating capacity in India to the installed power-generating capacity is about 10.21% presently (Table 1), surplus gas supplies are not available for power plants. Diesel-based thermal power plants can be set up quickly as compared to coal-based power plants.

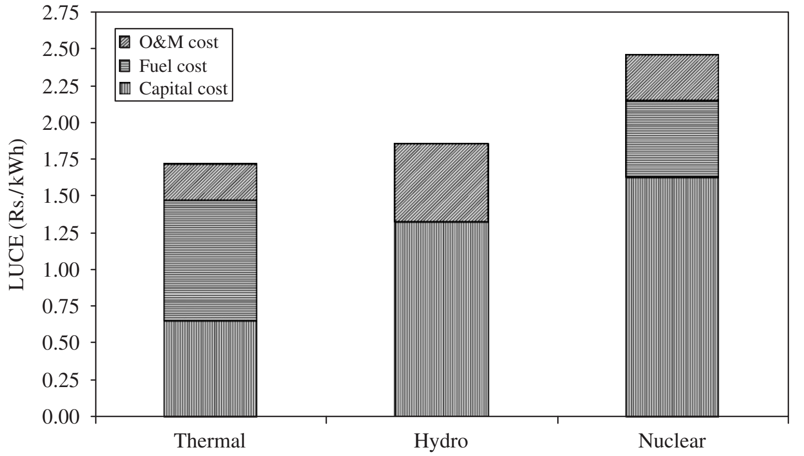

Fig. 5. Break up of generation cost of electricity for thermal, hydro and nuclear power plants.

Though such power plants are being preferred for captive power generation and also as a back up power supply option, yet the share of such projects was less than 1% in the total installed power-generating capacity in the country as on 3 April 2006 and which is not likely to increase in future. Moreover the financial viability of such projects would be affected adversely due to volatility in the prices of petroleum products in the international market in the last couple of years. Therefore, for the purpose of estimating the delivered cost of electricity at a remote and inaccessible area, the effective cost of generation of electricity has been considered as the one estimated for a typical CTPP for the purpose of further analysis in this study.

4.1.11. T&D losses

There is a large variation in the reported levels of T&D losses from state to state in the country (65.18% in Manipur to 17.16% in Tamilnadu during 2003–2004). This includes transformation losses and also unaccounted losses of electricity. As per available information even in cities such as Chandigarh (39.06%) and Delhi (43.66%) T&D losses are quite high. The national average T&D losses for 2004–2005 are reported to be at 32.53% [21]. One of the implications of high T&D losses is that for each unit of delivered electricity, $[1/(1-\mathrm{TDL})]$ units of electricity are to be generated at the bus bars of the power plant with TDL representing the T&D losses (including unaccounted losses) in fractions. Therefore, for delivering one unit of electricity at the point of consumption, 1.48 units of electricity are to be generated at the bus bars of the power plant due to average T&D losses of 32.53%. Accordingly, the effective cost of generation of electricity becomes Rs. 2.53/kWh.

4.2. Cost of transmission of electricity

The path traced by electricity through the transmission network from its point of generation to the distribution network is very difficult to trace in a large electricity transmission network such as one in India with five interconnected regional grids. Estimation of the transmission or wheeling cost per unit of electricity fed into a distribution network is therefore quite intricate. Considering the complexity of the issue, Andhra Pradesh Electricity Regulatory Commission, Hyderabad fixed the wheeling charges for electricity during 2002–2003 as Rs. 0.50/kWh [24] and the same has been assumed as the levelised unit cost of transmitting one unit of electricity ($\mathrm{LUCE_w}$) generated by a CTPP irrespective of the transmission path traced by electricity in this study.

4.3. Cost of distribution of electricity

The cost details of different components of electricity distribution network i.e. step down transformer (11 kV/440 V) in four different ratings (5, 25, 63 and 100 kVA), conductors for 11 kV distribution lines and low-tension (LT) lines that carry electricity to the point of consumption (three-phase four-wire and single-phase two-wire) considered in this study are given in Table 8. The LUCE distribution ($\mathrm{LUCE_d}$) can be estimated by using the following expression:

$$\mathrm{LUCE_d} = \frac{[C_\mathrm{T} + 0.5 \times x \times C_{11} + 0.25 \times x(C_{4\mathrm{W}} + C_{2\mathrm{W}})](\mathrm{CRF} + m)}{8760 \times P_\mathrm{PL} \times \mathrm{LF}}, \tag{6}$$

where C_T is the cost of step-down transformer (11 kV/440 V), x the total length by which the electricity distribution lines have to be extended, C_{11} the unit cost of 11 kV distribution line, C_{4W} the unit cost of three-phase four-wire distribution line, C_{2W} the unit cost of single-phase two-wire distribution line, m the fraction of the total capital cost of distribution system towards O&M of distribution network, P_{PL} the peak load in the village/villages for which the entire distribution system has to be designed and LF the load factor in the village or cluster of villages to be served by the new distribution network. $LUCE_d$ has been estimated for different values of the total distance (x) of extended distribution network (up to 25 km) from the point of the existing T&D network (which has been considered as 11 kV electricity distribution line in this study though in certain cases it could be 33 kV electricity distribution line). Variation of load factors in the villages in the range (0.1–0.8) and different peak loads (5–100 kW in hilly terrain and 25–100 kW in plain terrain) have been considered in this study. While the cost of distribution of electricity has been estimated in the range of Rs. 0.15–20.47/kWh in the plain terrain (Table 9), it varies in the range of Rs. 0.31–228.11/kWh in hilly terrain (Table 10) depending on the above-mentioned factors.

It is observed from Tables 9 and 10 that the cost of distributing electricity increases with increase in distance of new distribution network to be established, reduction in the peak load of the village/villages, and reduction in the load factor. For a large village (or a cluster of smaller villages) with peak load of 100 kW and a load factor of 0.8, the cost of distribution is estimated at Rs. 0.15/kWh if the length of the new electricity distribution network to be established is 5 km in a plain terrain. On the other hand, the estimated cost of distribution of electricity in a plain terrain increases to Rs. 20.47/kWh if the peak load is only 25 kW, the load factor is merely 0.1 and the total length of new electricity distribution network to be established is 25 km. While high load factors in the villages is an indicator of presence of some small-scale industrial load, the low load factor means that the requirement of electricity is predominantly for lighting.

In comparison to the villages in a plain terrain, the villages in the hilly terrain have relatively lower number of households and the same are dispersed. Moreover, these villages practically do not have any industrial and commercial loads. Such villages are

Table 8
Cost details of LT distribution network

Rating of distribution transformers (kVA) for voltage step down from 11 kV to 440 V	Unit	Cost (Rs.) for	
		Plain terrain	Hilly terrain
5	Rs.	—	33,765
25	Rs.	62,610	73,538
63	Rs.	90,554	106,360
100	Rs.	105,454	123,860
11 kV line with conductors	Rs./km	104,954	256,452
LT line 3-phase 4-wire with conductors	Rs./km	108,485	262,430
LT line single-phase 2-wire with conductors	Rs./km	119,335	217,322

Source: [37].

Table 9
Cost of distribution of electricity in plain terrain

Distance of village from existing 11 kV line (km)	Peak load (kW)	Estimated cost of distribution of electricity (Rs./kWh) with a load factor of					
		0.1	0.2	0.3	0.4	0.6	0.8
5	25	4.46	2.23	1.49	1.11	0.74	0.56
	63	1.85	0.93	0.62	0.46	0.31	0.23
	100	1.19	0.60	0.40	0.30	0.20	0.15
8	25	6.86	3.43	2.29	1.72	1.14	0.86
	63	2.80	1.40	0.93	0.70	0.47	0.35
	100	1.79	0.90	0.60	0.45	0.30	0.22
10	25	8.46	4.23	2.82	2.12	1.41	1.06
	63	3.44	1.72	1.15	0.86	0.57	0.43
	100	2.19	1.10	0.73	0.55	0.37	0.27
12	25	10.06	5.03	3.35	2.52	1.68	1.26
	63	4.07	2.04	1.36	1.02	0.68	0.51
	100	2.59	1.30	0.86	0.65	0.43	0.32
15	25	12.46	6.23	4.15	3.12	2.08	1.56
	63	5.03	2.51	1.68	1.26	0.84	0.63
	100	3.19	1.60	1.06	0.80	0.53	0.40
20	25	16.46	8.23	5.49	4.12	2.74	2.06
	63	6.61	3.31	2.20	1.65	1.10	0.83
	100	4.19	2.10	1.40	1.05	0.70	0.52
25	25	20.47	10.23	6.82	5.12	3.41	2.56
	63	8.20	4.10	2.73	2.05	1.37	1.03
	100	5.19	2.60	1.73	1.30	0.87	0.65

characterized by relatively small peak loads (up to 5 kW), low load factors due to the fact that electricity would be mainly required for lighting in the evening for a few hours (about 0.1) and large total distance of new distribution network that may have to be established for providing electricity access to a remote village (up to 25 km or even more). In addition, the initial investment required for establishing new electricity distribution network is relatively higher in the hilly terrain (as compared to plain terrain) primarily due to lack of logistics and dependence on manual labor. As expected, the differences in the values of cost of distribution of electricity for plain and hilly terrains are more prominent at low peak loads and low load factors.

In a village in the hilly terrain requiring establishment of a new network of 25 km, the cost of distributing electricity is estimated to be as high as Rs. 228.11/kWh if the peak load is only 5 kW and the load factor is merely 0.1. It is worth mentioning that for a small remote village with only 20 households requiring domestic lighting for 3–4 h in the evening/night the peak load and load factors will be in the same range and thus the cost of distribution of electricity is likely to be prohibitively high. It clearly establishes the financial un-viability of providing electricity through grid connectivity to small remote villages in hilly and other inaccessible areas.

Table 10
Cost of distribution of electricity in hilly terrain

Distance of village from existing 11 kV line (km)	Peak load (kW)	Estimated cost of distribution of electricity (Rs./kWh) with a load factor of					
		0.1	0.2	0.3	0.4	0.6	0.8
5	5	46.61	23.30	15.54	11.65	7.77	5.83
	25	9.61	4.81	3.20	2.40	1.60	1.20
	63	3.91	1.95	1.30	0.98	0.65	0.49
	100	2.50	1.25	0.83	0.62	0.42	0.31
8	5	73.83	36.92	24.61	18.46	12.31	9.23
	25	15.06	7.53	5.02	3.76	2.51	1.88
	63	6.07	3.04	2.02	1.52	1.01	0.76
	100	3.86	1.93	1.29	0.96	0.64	0.48
10	5	91.98	45.99	30.66	23.00	15.33	11.50
	25	18.69	9.34	6.23	4.67	3.11	2.34
	63	7.51	3.76	2.50	1.88	1.25	0.94
	100	4.76	2.38	1.59	1.19	0.79	0.60
12	5	110.13	55.07	36.71	27.53	18.36	13.77
	25	22.32	11.16	7.44	5.58	3.72	2.79
	63	8.95	4.48	2.98	2.24	1.49	1.12
	100	5.67	2.84	1.89	1.42	0.95	0.71
15	5	137.36	68.68	45.79	34.34	22.89	17.17
	25	27.76	13.88	9.25	6.94	4.63	3.47
	63	11.11	5.56	3.70	2.78	1.85	1.39
	100	7.03	3.52	2.34	1.76	1.17	0.88
20	5	182.73	91.37	60.91	45.68	30.46	22.84
	25	36.84	18.42	12.28	9.21	6.14	4.60
	63	14.71	7.36	4.90	3.68	2.45	1.84
	100	9.30	4.65	3.10	2.33	1.55	1.16
25	5	228.11	114.05	76.04	57.03	38.02	28.51
	25	45.91	22.96	15.30	11.48	7.65	5.74
	63	18.31	9.16	6.10	4.58	3.05	2.29
	100	11.57	5.79	3.86	2.89	1.93	1.45

4.4. Delivered cost of electricity

The estimated cost of delivered electricity in the remote and inaccessible villages in plain and hilly terrains can be estimated using the following expression:

$$\mathrm{LUCE_{dl}} = \mathrm{LUCE_g} + \mathrm{LUCE_W} + \mathrm{LUCE_d}. \tag{7}$$

The estimated values of the $\mathrm{LUCE_{dl}}$ for plain and hilly terrains are presented in Tables 11 and 12, respectively. While the delivered cost of electricity is estimated to be Rs. 3.18/kWh for a village or a cluster of villages located in plain terrain that requires the distribution network to be extended by 5 km and having a peak load of 100 kW with load factor of 0.8, the same is estimated to be Rs. 23.50 for a village or a cluster of villages in

plain terrain that requires the distribution network to be extended by 25 km and having a peak load of 25 kW with load factor of 0.1. On the other hand for a village or a cluster of villages located in the hilly and inaccessible areas the corresponding values of the delivered cost of electricity are estimated to be, respectively Rs. 3.35/kWh (100 kW peak load, 0.8 load factor and requiring 5 km long new distribution network) and Rs. 231.14 (5 kW peak load, 0.1 load factor and requiring 25 km long new distribution network). The variation in the values of delivered cost of electricity for 25 kW peak loads in plain terrain and 5 kW hilly terrains are also presented in Figs. 6 and 7.

5. Estimation of electrical loads in remote villages

An elaborate census exercise is conducted after a gap of every 10 years in India. The last census in India was conducted in 2001. Apart from a lot of demographic information, such a nationwide exercise, covering all villages and habitations in the country, also provides information that can be used for planning of developmental activities in the villages.

Table 11
Delivered cost of electricity in plain areas

Cost of generation (Rs./kWh):	1.71
T&D losses (%):	32.53[a]
Effective cost of generation (Rs./kWh):	2.53
Transmission cost (Rs./kWh):	0.50
Cost of electricity at distribution network (Rs./kWh)	3.03

Distance from 33 kV line (km)	Peak load (kW)	Delivered cost of electricity (Rs./kWh) with a load factor of					
		0.1	0.2	0.3	0.4	0.6	0.8
5	25	7.49	5.26	4.52	4.15	3.78	3.59
	63	4.89	3.96	3.65	3.50	3.34	3.27
	100	4.23	3.63	3.43	3.33	3.23	3.18
8	25	9.90	6.46	5.32	4.75	4.18	3.89
	63	5.84	4.44	3.97	3.74	3.50	3.38
	100	4.83	3.93	3.63	3.48	3.33	3.26
10	25	11.50	7.27	5.85	5.15	4.44	4.09
	63	6.47	4.75	4.18	3.89	3.61	3.46
	100	5.23	4.13	3.77	3.58	3.40	3.31
12	25	13.10	8.07	6.39	5.55	4.71	4.29
	63	7.11	5.07	4.39	4.05	3.71	3.54
	100	5.63	4.33	3.90	3.68	3.47	3.36
15	25	15.50	9.27	7.19	6.15	5.11	4.59
	63	8.06	5.55	4.71	4.29	3.87	3.66
	100	6.23	4.63	4.10	3.83	3.57	3.43
20	25	19.50	11.27	8.52	7.15	5.78	5.09
	63	9.65	6.34	5.24	4.69	4.14	3.86
	100	7.23	5.13	4.43	4.08	3.73	3.56
25	25	23.50	13.27	9.86	8.15	6.45	5.59
	63	11.24	7.14	5.77	5.09	4.40	4.06
	100	8.23	5.63	4.77	4.33	3.90	3.68

[a]Average national transmission and distribution losses during 2003–2004 [21].

Table 12
Delivered cost of electricity in hilly areas

Cost of generation (Rs./kWh)	1.71
T&D losses (%)	32.53[a]
Effective cost of generation (Rs./kWh)	2.53
Transmission cost (Rs./kWh)	0.50
Cost of electricity at distribution network (Rs./kWh)	3.03

Distance from 33 kV line (km)	Peak load (kW)	Delivered cost of electricity (Rs./kWh) with a load factor of					
		0.1	0.2	0.3	0.4	0.6	0.8
5	5	49.64	26.34	18.57	14.69	10.80	8.86
	25	12.65	7.84	6.24	5.44	4.64	4.24
	63	6.94	4.99	4.34	4.01	3.69	3.52
	100	5.53	4.28	3.87	3.66	3.45	3.35
8	5	76.87	39.95	27.65	21.49	15.34	12.26
	25	18.09	10.56	8.05	6.80	5.54	4.92
	63	9.10	6.07	5.06	4.55	4.05	3.79
	100	6.89	4.96	4.32	4.00	3.68	3.52
10	5	95.02	49.03	33.70	26.03	18.37	14.53
	25	21.72	12.38	9.26	7.71	6.15	5.37
	63	10.55	6.79	5.54	4.91	4.29	3.97
	100	7.80	5.42	4.62	4.23	3.83	3.63
12	5	113.17	58.10	39.75	30.57	21.39	16.80
	25	25.35	14.19	10.47	8.61	6.75	5.82
	63	11.99	7.51	6.02	5.27	4.53	4.15
	100	8.71	5.87	4.92	4.45	3.98	3.74
15	5	140.39	71.71	48.82	37.37	25.93	20.20
	25	30.80	16.92	12.29	9.98	7.66	6.50
	63	14.15	8.59	6.74	5.81	4.89	4.42
	100	10.07	6.55	5.38	4.79	4.21	3.91
20	5	185.77	94.40	63.95	48.72	33.49	25.88
	25	39.87	21.45	15.31	12.24	9.17	7.64
	63	17.75	10.39	7.94	6.71	5.49	4.87
	100	12.34	7.69	6.13	5.36	4.58	4.20
25	5	231.14	117.09	79.07	60.06	41.05	31.55
	25	48.95	25.99	18.34	14.51	10.69	8.77
	63	21.35	12.19	9.14	7.61	6.09	5.32
	100	14.60	8.82	6.89	5.93	4.96	4.48

[a]Average national transmission and distribution losses during 2003–2004 [21].

The detailed results of village census data for 2001 census are not yet available and therefore, the village census data for 1991 census has been utilized to determine state wise number of villages in all states and union territories that were not having access to electricity at the time of survey i.e. 1991. This information has been tabulated and presented in Table 13.

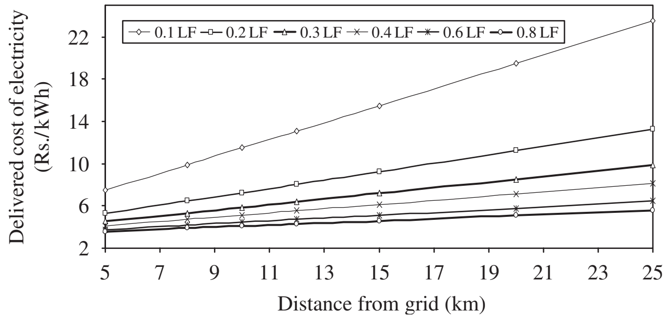

Fig. 6. Delivered cost of electricity in plain areas (for 25 kW peak load) by grid extension.

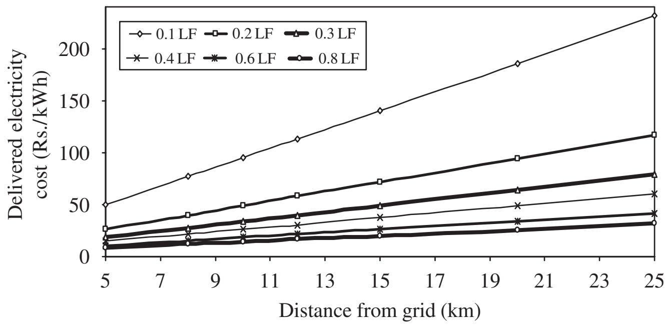

Fig. 7. Delivered cost of electricity in hilly areas (for 5 kW peak load) by grid extension.

Estimation of the total average household peak electrical load has been made based on the electrical loads in the households for lighting, fans, refrigerator, television and transistor; lighting of street/pathway; water pumping and other loads that could be for shops etc. It is estimated that the total average household peak electrical load could be about 0.675 kW as per details presented in Table 14. The total connected electrical load of a village that is to be met by the grid supplied electricity or through decentralized generation option can be estimated based on the number of households (as per 1991 census) and the total average peak electrical load of a household. A substantial fraction of villages not having access to electricity have small number of households. Table 15 presents the results of number of villages in the undivided state of Bihar (now Bihar and Jharkhand) that are likely to have the estimated peak loads in the range of 10–100 kW. It is observed that out of a total 77,698 villages that were not having access to electricity (as per 1991 census) in Bihar, about 55% (43,054 villages) are likely to have estimated peak electrical load of less than 100 kW. Among the villages that are likely to have peak electrical load of up to 100 kW, about 65.30% of villages are likely to have the estimated peak load of up to 50 kW. Such villages with peak electrical loads up to 50 kW may be the potential villages that need to be considered for providing electricity through the renewable energy-based decentralized electricity generation options. However, suitability of decentralized electricity generation option for such villages would largely depend on how the value of the LUCE for decentralized generation options compares with grid extension option.

Table 13
Villages having access to electricity (as per 1991 census)

Name of State/UT	Total villages	Uninhabited villages	Without electricity access	With electricity access as per 1991 census
Andhra Pradesh	27,999	4204	0	23,795
Arunachal Pradesh	3649	21	2542	1086
Assam	25,590	905	11,557	13,128
Bihar	77,698	10,185	43,054	24,459
Goa	383	0	32	351
Gujarat	18,509	850	0	17,659
Haryana	6988	229	0	6759
Himachal Pradesh	19,388	2391	369	16,628
Jammu and Kashmir	Data not available			
Karnataka	29,194	1	2923	26,270
Kerala	1384	0	1	1383
Madhya Pradesh	76,220	4694	15,528	55,998
Maharashtra	43,025	4244	5	38,776
Manipur	2228	48	928	1252
Meghalaya	5629	155	3775	1699
Mizoram	785	87	466	232
Nagaland	1225	8	91	1126
Orissa	51,061	4343	21,479	25,239
Punjab	12,795	0	364	12,431
Rajasthan	39,810	1921	15,218	22,671
Sikkim	453	6	71	376
Tamilnadu	16,780	946	149	15,685
Tripura	856	1	239	616
Uttar Pradesh	123,950	563	43,522	79,865
West Bengal	40,890	2979	21,399	16,512
Andaman and Nicobar	547	43	258	246
Chandigarh	25	0	0	25
Dadra and Nagar Haveli	71	1	0	70
Daman and Diu	24	0	0	24
Delhi district	209	10	4	195
Lakshadweep	23	16	0	7
Pondicherry	277	14	0	263
All India total	627,665	38,865	183,974	404,826

6. Cost of electricity from decentralized generation options

The cost of generation of electricity from decentralized generation options in Indian conditions has been studied and reported in the literature. Sinha and Kandpal [3] found that for small and isolated villages characterized by low load factors, renewable energy-based decentralized technologies can be viable alternatives for rural electrification in comparison to the extension of the grid. The cost of generation from biomass gasifier-based option has been examined in Indian context [25–27]. The cost of electricity generated form biomass gasifier-based project was found to be high in view of its low-capacity utilization and the same was estimated at Rs. 9.35/kWh in 1999 for a 500 kW biomass

Table 14
Estimation of average connected electrical loads of households in rural areas

Load	No. of units	Wattage (W)	Coverage[a] (fraction)	Connected load (W)
Domestic lighting	3	40	1	120
Street lights	1	40	0.5	20
Fans for cooling	1	100	0.5	50
Refrigeration	1	250	0.15	37.5
Television[b]	1	200	0.316	63.2
Transistor[c]	1	5	0.351	1.755
Water pumping	1	3730	0.1	373
Other loads	1	100	0.1	10
Estimated total average connected electrical load of household (kW)				0.675

[a]Depending on the number of households in a village, a coverage fraction of 1 implies that each household will have 3 domestic incandescent lamps each of 40 W rating. Coverage fraction of 0.5 for street light means that between two households there will be one incandescent lamp of 40 W.

[b]Based on 31.6% and 35.1% households owning televisions and radio sets in rural areas as per 2001 census data for India.

gasifier operating at about 15% PLF [25]. Studies on techno-economics of PV-based decentralized generation [2,28,29] have found that on the basis of the LUCE, PV-based decentralized electricity generation is not viable as compared to grid extension option even in remote areas and it becomes viable only if the grid is to extended by about 20 km [29]. Kolhe et al. [30] analyzed the issue of financial viability of a stand-alone PV system in comparison to a diesel generating set-based decentralized generation and reported that PV projects are financially attractive for daily energy demands of up to 15 kWh. Banerjee [31] has undertaken a detailed analysis for estimating LUCE for different decentralized generation technologies in India.

Unit capital cost and LUCE for a variety of systems for decentralized generation and supply of electricity in remote and inaccessible areas in India (such as biomass gasifier-based dual-fuel engines, diesel generating systems, micro-hydro projects, PV systems and small wind electric generators) installed in field have been estimated in the recent years by the authors [13,32–34] and the results reported therein are summarized in Table 16.

7. Comparison of unit capital cost and cost of delivered electricity

A comparison of unit capital cost (Rs. /kW) of different electricity generating technologies, both conventional i.e. coal thermal, large hydro-electric, nuclear and diesel generating sets and renewable energy-based technologies i.e. biomass gasifier-based engine-generator sets (dual-fuel and 100% producer gas), micro-hydro, PV and small wind electricity generators (based on results presented in Tables 7 and 16 and Appendices A.2 and A.3) has been presented in Fig. 8. In terms of the unit capital cost, diesel generating set-based systems appear to be the most attractive followed by coal thermal, nuclear and large HPP. Among renewable energy-based options considered in this study, PV is the most expensive and biomass gasifier-based systems

Table 15
District wise details of estimated average connected electrical load in villages

Name of district	Total villages	Un-electrified villages	Un-electrified villages with estimated connected electrical load (kW)										
			Up to 10	10–20	20–30	30–40	40–50	50–60	60–70	70–80	80–90	90–100	Total up to 100 kW
Patna	1428	203	1	6	12	17	10	17	11	19	12	7	112
Nalanda	1057	105	1	5	7	7	11	14	7	6	6	4	68
Bhojpur	2351	860	51	81	71	81	71	68	59	55	34	37	608
Rohtas	3773	1345	125	158	147	146	144	109	89	92	65	48	1123
Aurangabad	1848	693	44	67	108	94	67	67	51	39	28	18	583
Jehanabad	918	238	7	11	20	28	16	14	15	17	9	11	148
Gaya	2896	1229	96	132	126	154	131	102	87	66	55	47	996
Nawada	1091	225	11	18	24	24	19	21	14	16	9	8	164
Saran	1767	915	5	77	44	54	48	59	48	62	54	60	511
Siwan	1535	988	45	45	64	81	74	74	66	65	57	46	617
Gopalganj	1537	869	54	79	70	72	71	68	60	57	48	37	616
Pashchim Champaran	1486	959	25	42	51	51	71	54	50	63	46	48	501
Purba Champaran	1323	824	14	27	22	38	24	43	32	35	34	30	299
Sitamarhi	1037	604	7	15	16	10	12	17	24	37	14	23	175
Muzaffarpur	1796	651	30	35	33	45	36	39	36	42	30	31	357
Vaishali	1569	534	46	46	56	37	35	23	38	21	24	29	355
Begusarai	1190	195	21	18	14	12	43	10	13	12	2	3	148
Samastipur	1237	505	24	28	23	28	22	34	15	14	27	19	234
Darbhanga	1269	541	19	16	27	32	26	23	21	22	30	19	235
Madhubani	1111	516	12	16	15	19	18	18	20	18	26	21	183
Saharsa	1012	663	10	22	19	19	20	18	23	20	20	16	187
Madhepura	432	200	8	11	9	7	8	8	5	4	2	2	64
Purnia	1281	836	47	56	50	41	40	43	44	33	25	22	401
Katihar	1543	939	46	54	66	64	54	73	38	46	35	47	523
Khagaria	301	114	0	3	2	1	2	2	1	3	1	6	21
Munger	3148	1440	197	224	156	136	102	87	62	48	47	57	1116

Bhagalpur	3629	1465	173	233	181	148	101	82	76	68	48	30	1140
Godda	2304	1313	200	212	111	181	95	93	62	71	57	39	1121
Sahibganj	3076	2119	324	414	396	120	160	245	5	104	64	45	1877
Dumka	4090	3469	298	642	567	512	365	312	182	148	122	113	3261
Deoghar	2704	1856	356	409	307	257	151	90	80	70	36	28	1784
Dhanbad	1479	827	59	107	86	82	69	61	53	38	36	26	617
Giridih	3149	2200	271	382	299	269	192	168	113	78	73	57	1902
Hazaribag	3819	2554	357	381	320	260	223	67	241	125	85	74	2133
Palamu	3581	2395	264	274	252	246	219	172	154	28	207	108	1924
Lohardaga	354	209	8	21	26	32	13	16	11	16	9	10	162
Gumla	1398	1260	17	58	85	122	117	111	109	82	91	78	870
Ranchi	2057	1579	50	119	169	180	168	147	117	105	90	82	1227
Purbi Singhbhum	1750	1161	103	153	147	148	113	99	81	63	47	42	996
Pashchimi Singhbhum	2859	2324	125	258	272	251	234	220	166	149	106	108	1889
Araria	742	535	14	16	27	10	9	20	23	20	11	18	168
Kishanganj	771	597	23	34	40	30	34	39	21	32	22	31	306
Total	77,698	43,054	3588	5005	4537	4146	3438	3047	2423	2109	1844	1585	31,722
% of un-electrified villages with connected load up to 100 kW			11.31	15.78	14.30	13.07	10.84	9.61	7.64	6.65	5.81	5.00	

Table 16
Unit capital cost and levelised unit cost of electricity based on some decentralized generation technologies deployed in India

S. No.	Name of technology	Range of unit capacity of decentralized generation technology (kW)	Range of unit capital cost of decentralized generation technology (Rs./kW)	Estimated range of levelised unit cost of electricity (Rs./kWh)
1.	Biomass gasifiers			
a.	Dual fuel engine system	5–40	122,000–44,000	25.00–13.14[a]
b.	100% producer gas engine system	9–40	95,000–75,000	18.53–15.02[a]
2.	Diesel generating set	5–40	35,000–16,500	21.38–13.51[a]
3.	Small hydro power	10–100	124,000–216,000	4.56–8.31[b]
4.	Photovoltaic system	2.5–25.0	308,000–279,000	47.14–42.67[c] 37.26–33.73[d] 32.32–29.26[e]
5.	Small wind electric generators	1–50	203,000–67,000	44.17–6.30

[a]For plant load factor of 25%.
[b]For plant load factor of 40%.
[c]Annual average daily global solar radiation 4.72 kWh/m^2 and net array output of 1086 kWh/kW$_p$.
[d]Annual average daily global solar radiation 5.52 kWh/m^2 and net array output of 1374 kWh/kW$_p$.
[e]Annual average daily global solar radiation 4.89 kWh/m^2 and net array output of 1584 kWh/kW$_p$.

(dual-fuel engine-generator set and 100% producer gas engine-generator set) option is the most attractive option in terms of unit capital cost.

In terms of the LUCE, coal thermal option is the most attractive options among the conventional electricity-generating options (Appendices A.1–A.3). The estimated cost of electricity generated from a CTPP and delivered to a remote village varies in the range of Rs. 3.18–23.50/kWh in plain terrain (Table 11) depending on the factors discussed in Section 4.4. In the hilly terrain the cost of delivered electricity is estimated to vary in the range of Rs. 3.35–231.14/kWh (Table 12). When these values of the estimated cost of delivered electricity through the grid extension option in plain and hilly terrains are compared with the values of LUCE (Rs. 4.56–47.14/kWh) of decentralized generation options (Table 16), it is observed that the decentralized electricity generation options may emerge financially attractive in comparison to grid extension option in some potential areas.

8. Potential areas for decentralized electricity supply options

8.1. Critical distance of grid extension

The estimated values of the LUCE from the decentralized electricity generation options under Indian conditions is found to vary in the range of Rs. 4.56–47.14/kWh depending on the technology, resource availability and other operating factors.

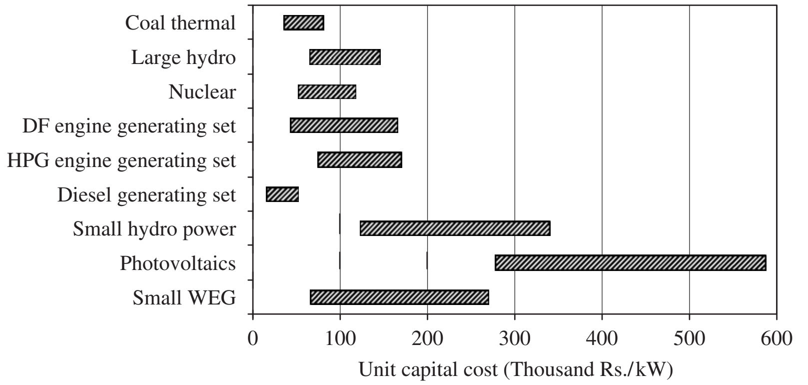

Fig. 8. Comparison of the unit capital cost of different electricity-generating technologies.

The values of the LUCE are found to be more or less independent of the distance by which the distribution network has to be extended from the existing point of electricity distribution network in the case of decentralized electricity supply options. On the other hand, in the case of grid extension option, the values of the LUCE have direct dependence on the distance by which electricity distribution network is to be extended. Therefore, out of these two options for providing electricity, the decentralized electricity generation option cannot compete with grid extension option (in terms of the delivered cost of electricity) for villages that require grid extension from the existing electricity distribution network by a distance below a certain critical value. The decentralized electricity generation options become financially competitive only and beyond this critical value of grid extension.

8.2. Estimation of critical distance of grid extension

Using Eqs. (6) and (7) the following expression for the value of critical distance of grid extension x_c can be derived:

$$x_c = \frac{8760 \times P_{PL} \times LF(LUCE_{dc} - LUCE_g - LUCE_W) - C_T}{(CRF + m)[0.5 \times C_{11} + 0.25(C_{4W} + C_{2W})]}. \tag{8}$$

The results of some typical calculations for the critical distance of grid extension in plain (peak load 25 kW) and hilly (peak load 5 kW) terrains for different load factors (0.1–0.8) are presented in Figs. 9 and 10, respectively. As expected, for a fixed value of peak load and a particular value of delivered cost of electricity from decentralized generation option, the value of critical distance of grid extension increases with increase in the load factor. For smaller values of peak loads and low load factors the critical distances of grid extension is rather small thus implying that in such situations the renewable energy-based decentralized electricity generation options may be financially attractive to grid extension option even if the required distance of grid extension is small.

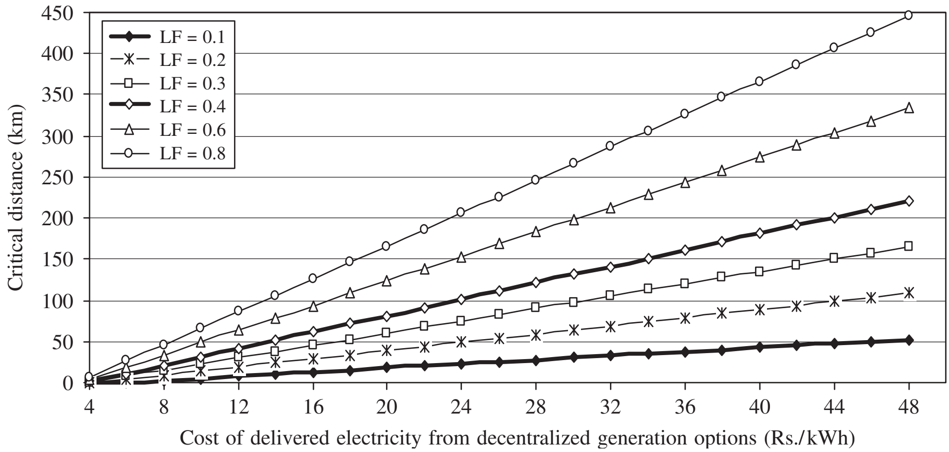

Fig. 9. Critical distance of grid extension for electricity delivered by decentralized electricity generation options in plain areas (for 25 kW peak load).

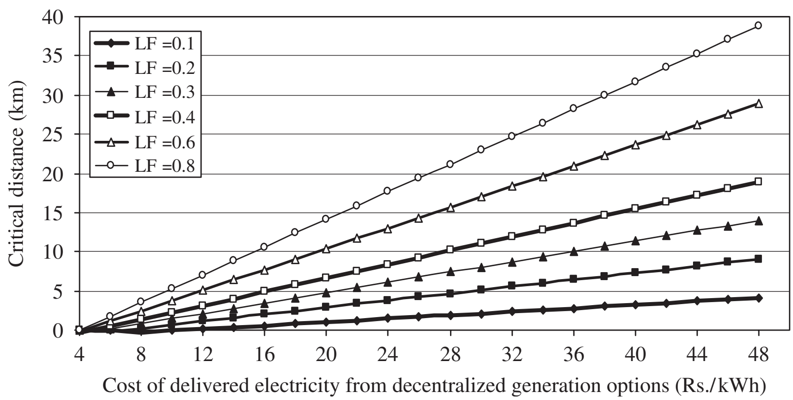

Fig. 10. Critical distance of grid extension for electricity delivered by decentralized electricity generation options in hilly areas (for 5 kW peak load).

8.3. Potential areas for renewable energy-based decentralized electricity generation

In a village or a cluster of households all connected electrical loads would not draw power simultaneously. The statistical time staggering in the average capacity requirement of the power is significantly lower than the sum of the individually connected loads. Since in Indian villages the electrical loads are expected to be for lighting and operating devices for entertainment (such as television/transistor radio, etc.), the same are likely to remain switched on in the evening/night for about 5–6 h. Therefore, in this study, a uniform load factor of 0.8 has been assumed for estimating the capacity

requirement of the power supply system i.e. transformer to be set up in a village for extending the electricity distribution network. Based on the capacity requirement of power supply system, typical sizes of the transformers used in rural areas of India have been selected. Considering the number of households in the village and average number of hours for which electricity is likely to be used, typical load factors of the electricity supply system have been estimated. On the basis of (i) electrical load and load factor of the village, (ii) the values of the LUCE for different renewable energy-based decentralized electricity generation options for meeting the power requirement and relevant cost details of generation, and (iii) T&D costs for grid extension option based on a typical centralized power plant system, critical distances beyond which a particular decentralized electricity generation option would become financially attractive to grid extension option have been estimated and the results are presented in Table 17.

The resource for setting up the MHP is expected to be available only in hilly areas and it emerges out as a financially attractive and the preferred option in comparison to grid extension for as low a distance of grid extension as 2 km if the number of households in the village are less than 50. For villages having more than 50 households, the MHP option becomes viable if the electricity distribution grid is to be extended by about 15 km. MHP option may also become viable for shorter lengths of grid extension in case the PLF for MHP projects can be improved beyond 40%. The dual-fuel biomass gasifier-based power generating (DF BGPP) option is unlikely to be considered for villages in the plain terrain with less than 20 households. DF BGPP option for somewhat larger villages (15–30 households) may be the preferred option if the grid is to be extended by about 14–22 km or more in plain areas (depending on capacity requirement of power). For smaller villages (5–50 households) in hilly and other inaccessible area, DF BGPP option is expected to be the preferred option, if grid is to be extended

Table 17
Niche areas for renewable energy based decentralized electricity generation

No. households in village	Power generation capacity required (kW)	Distance of grid extension in km beyond which decentralized options become attractive					
		MHP	DF BGPP		SWEG		PV
		Hilly areas	Plain areas	Hilly areas	Plain areas	Hilly areas	Hilly areas
5	1	0	—	5.35	—	2.99	3.72
10	3	0.04	—	5.53	—	7.20	7.96
15	4	0	13.61	5.72	23.47	10.07	11.20
20	5	0.06	15.40	6.52	33.61	14.55	16.09
30	8	0.84	21.31	9.12	50.52	30.09	24.25
40	11	1.42	35.24	15.26	70.81	30.95	34.04
50	14	1.93	34.69	14.90	25.79	10.97	42.54
75	20	13.36	45.76	19.78	39.87	17.18	63.10
100	27	18.37	70.93	30.88	53.94	23.39	83.65
150	41	15.17	95.00	41.44	83.34	36.28	127.39

in the range of 5–15 km and micro hydro resource is not available. Small wind electric generators (annual mean wind speed greater than 6 m/s) and PV (annual average daily solar radiation on horizontal surface more than 5.5 kWh/m^2) options may be financially attractive in hilly and inaccessible areas for smaller villages (up to 20 households) in case grid is to be extended in the range of 3–16 km and micro hydro and DF BGPP options are not feasible (primarily due to unavailability of resources).

9. Conclusions

In 2004, about 19% villages in India did not have access to electricity due to inadequacies in generation, transmission and distribution. It is reported that it would not be financially viable to provide electricity access to more than 24,500 villages in the country due to (a) very small number of households in these villages resulting in un-economical loads, (b) poor load factors arising out of non-existent industrial/commercial loads, (c) and requirement of electricity predominantly for lighting and powering televisions and transistors, and (d) remoteness of villages in terms of their distance from the existing electricity distribution grid. The cost of delivered electricity to a village (with about 20 households, peak load of 5 kW and the load factor of 0.2) located at a distance of 5 km from the grid is estimated at Rs. 26.00/kWh. Such low peak loads and load factors are characteristics of the villages having small number of households requiring electricity predominantly for lighting application. The estimated delivered cost of electricity increases to Rs. 95/kWh if the required extension in distribution network is 10 km. The results of the calculations made in the study indicates that all renewable energy-based decentralized electricity supply options considered in this study (such as micro hydro, dual-fuel biomass gasifier systems, small wind electric generators and photovoltaics (PV)) could be financially attractive as compared to grid extension for providing access to electricity in such small remote villages. Micro hydro appears to the best option for hilly areas subject to availability of the resource and it should be the first choice for providing electricity in the remote and inaccessible areas. In fact in many situations for smaller villages it could be preferred even if the grid extension is required by 2 km only. Establishment of small-scale rural industries (such as flour and oil mills, paddy hullers, handicraft units, etc.) requiring electricity in such remote villages would further improve the financial attractiveness of micro hydro option by improving the PLF. Dual-fuel biomass gasifier-based decentralized electricity generating units are the second best option for providing electricity in remote villages (subject to availability of biomass on a sustainable basis) with number of households up to 75. Dual-fuel biomass gasifier-based power-generating systems are more cost effective when operated closer to their rated capacities. Therefore, similar to the case of micro hydro systems, development of commercial and industrial activities would go a long way in further improving the financial attractiveness of biomass gasifier-based electricity generation option in remote rural areas. PV and small wind electricity generators could be suited for providing electricity for lighting and powering televisions and transistor radios to small villages with households population of about 20 or less in remote and inaccessible areas (in case micro hydro and biomass resources are not available).

Acknowledgments

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Appendix A

Appendix A.1

See Table Al for the estimation of levelised unit cost of electricity for 2×500 MW Simhadri Thermal Power Project of NTPC.

Table A1
Estimation of levelised unit cost of electricity for 2×500 MW Simhadri Thermal Power Project of NTPC

Size of plant considered (kW)	1000
Estimated capital cost (Rs.)	36,500,000[a]
O&M cost as fraction of capital cost	0.04
Average cost of fuel oil at power plant (Rs./kl)	12,916.97[b]
Gross station heat rate (kcal/kWh)	2500[b]
Average cost of coal at power plant (Rs./tonne)	1060.24[b]
Specific fuel oil consumption (ml/kWh)	3.5[b]
Calorific value of fuel oil (kcal/l)	9787[a]
Heat supplied by oil (kcal)	34.25
Average calorific value of grade G coal (kcal/kg)	3508[a]
Heat to be supplied by coal (kcal)	2465.75
Specific coal consumption (kg/kWh)	0.70
Plant load factor	0.7482[c]
Auxiliary power consumption (fraction of generation)	0.0882[d]
Average cost of generation (Rs./kWh)	
Generation from power plant (kWh)	6,554,232
Auxiliary consumption (kWh)	578,083.2624
Generation at bus bar (kWh)	5,976,149
Annual capital cost (Rs.)	3,871,893
Total annual cost of coal consumed (Rs.)	4,884,439
Total annual cost of oil consumed (Rs.)	26,135
O&M cost (Rs.)	1,460,000
Total annual cost (Rs.)	10,242,466
Levelised unit cost of electricity (Rs./kWh)	1.71

[a] [19].
[b] [35].
[c] National average plant load factor for thermal power plants during 2004–2005 [12].
[d] Average auxiliary consumption for all thermal power projects [21].

Appendix A.2

For the estimation of levelised unit cost of generating electricity from Chamera II Hydro-electric Power Plant (3×100 MW) see Table A2.

Table A2
Estimation of levelised unit cost of generating electricity from Chamera II Hydro-electric Power Plant (3×100 MW)

Commissioning (month/year)	November 2003–March 2004
Approved cost (Million Rs.)	19,560.6[a]
Unit capital cost (Million Rs./MW)	65.202
Average O&M cost as fraction of capital cost	0.04
Plant load factor (fraction)	0.57[b]
Annual capital cost[c] (Rs.)	6,576,219
Annual O&M cost (Rs.)	2,608,080
Total annual cost (Rs.)	9,184,299
Auxiliary power consumption (fraction of generation)	0.0053[d]
Net electricity generation (kWh/MW of plant capacity)	4,966,736
Levelised unit cost of generation (Rs./kWh)	1.84

[a] [35].
[b] Estimated based on the month wise designed energy output of the project as given in [35].
[c] For discount rate = 0.10 and useful life of 50 years.
[d] Average auxiliary consumption for all hydro-electric power projects [21].

Appendix A.3

See Table A3 for the estimation of levelised unit cost of electricity generation from typical nuclear power plants in India.

Table A3
Estimation of levelised unit cost of electricity generation from typical nuclear power plants in India

Unit size (MW)	220	540
Estimated cost (Rs./MW)	90,991,613[a]	82,316,731[b]
Plant load factor (fraction)	0.738[c]	0.738[c]
Auxiliary power consumption (fraction of generation)	0.1136[d]	0.1136[d]
Generation from power plant (kWh/MW of plant capacity)	6,464,880	6,464,880
Auxiliary consumption (kWh/MW of plant capacity)	734,410.37	734,410.37
Net generation (kWh/MW of plant capacity)	5,730,469.6	5,730,469.6
Annual capital cost[e] (Rs.)	9,304,749	8,417,660
Annual fuel and O&M cost as fraction of capital cost	0.2[f]	0.2[f]
Annual cost of uranium and heavy water	2,971,755	2,502,637
Annual O&M cost	1,819,832	1,646,334
Total annual cost (Rs.)	14,096,336	12,566,633
Levelised unit cost of generation (Rs./kWh)	2.46	2.19

[a] Inclusive of cost of initial uranium and heavy water loading in capital cost [18].
[b] [23].
[c] Average plant load factor for nuclear power plants [21].
[d] Average auxiliary consumption for all nuclear power projects [21].
[e] For discount rate = 0.10 and useful life of 40 years.
[f] [18].

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